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ELECTROMAGNETIC RADIATION IN ACCELERATORS

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/Figures referred to are appended./

Present-day particle accelerators (cyclotrons, betatrons, synchrotrons, and others) attain energies up to several hundred million electron volts.

At higher energies of 100-1,000 Mev, one should expect many new physical effects. At present, we are striving to raise the energy level and also to solve the problem of thorough utilization of the range of energies already obtained (100-400 Mev).

Of the new physical effects discovered at high energies in the accelerators and discussed in the literature we shall devote our attention to one new physical effect peculiar to energies around 100 Mev. We have in mind the effect of electromagnetic radiation of fast relativistic electrons in betatron-type accelerators. It is interesting that at the indicated energies a noticeable part of the electron radiation occurs in the visible portion of the spectrum of electromagnetic waves.

This circumstance is very remarkable. Not long ago the 50th anniversary of the discovery of the electron was observed. However, in all these 50 years it was necessary to be satisfied only with indirect evidence of the presence of the electron. All experiments with electrons depended on secondary effects of electrons.

Indeed, all experiments with electron beams in vacuum tubes led finally to the observation of luminescence on the screens or the wall of the tube. But the observed luminescence appears not at all to be the luminescence of electrons but rather the luminescence of molecules or atoms activated by them. "Observing" electrons in counters can be spoken of only in a conditional sense, since in the counters the particles are registered but are by no means observed. We do not observe particles in the Wilson cloud chamber either; we see only the traces of the particles. In the thick-layer photo-plate process of L. V. Mysovskiy and A. P. Zhdanov we have only traces also; there are no direct appearances of particles. Particles are only traced on the photo plates.

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Only recently was direct electron luminescence discovered. The matter concerns the discovery of the Cherenkov effect. Here we actually have luminescence of the electrons themselves, but still with certain reservations. For Cherenkov electron luminescence, the presence of a medium is very essential. This radiation, as is known, takes place when the velocity of the electron surpasses the phase velocity of light in the surrounding medium, somewhat similar to certain effects in gas dynamics. In gas dynamics, certain peculiar effects will take place (shock waves) if the velocity of motion surpasses a certain characteristic velocity, namely the effective speed of sound. Thus, for shock waves as well as for the Cherenkov effect, the presence of a medium with definite characteristics appears decisive. Therefore the name put forth by I. E. Tamm for the Cherenkov electron -- "humming electron" -- seems very applicable since this name fits the essential meaning of the surrounding medium.

The only case where we see "pure" radiation of the electrons themselves is in the radiation of electrons in accelerators. Therefore, it appears correct to call the direct radiation of the electrons in accelerators as "the luminescent electron" effect, understanding by this in the general case the whole radiated spectrum and not only the visual radiation.

The presence of radiation from fast particles in the betatron type of accelerator was shown in 1944 by the Soviet physicists D. Ivanenko and I. Pomeranchuk. Further theory was developed by other Soviet and US scientists.

Experimentally, the radiation of electrons in a betatron was indirectly recorded by Blewett in 1946, and finally a "luminescent electron" was observed visually by Pollock's followers in 1947. The emission of electromagnetic radiation by particles moving in accelerators likewise is of immediate practical significance.

According to classical electrodynamics, charged accelerated particles lose a part of their energy in the form of radiation. As a consequence of this, particles moving in accelerators can fall out of correct phase with the accelerating field, which leads to a disruption of the normal operation of the accelerator. It is interesting, therefore, to explain the influence of this radiation on the character of the motion of the particles in the accelerator.

We shall give a short report of the basic works in which the radiation of charged particles in accelerators is studied, and bring forth certain interesting experimental data relating to this group of problems.

Radiation and Limits of Energy Attainable in Accelerators

The presence of energy losses in radiation can limit the maximum attainable energy in an accelerator. Even though the limiting energy of the accelerated particles in various types of accelerators is determined by various factors, let us selectively examine all basic types of accelerators for decisive circumstances of interest.

As is known, in simple (nonrelativistic) cyclotrons, used for acceleration of heavy particles, the maximum energy of the accelerated particles is limited by the relativistic increase in mass of the particle. For the proton, for example, an increase in mass of 10 percent takes place even at 100 Mev. As we will see below, at such energies the radiation of heavy particles is not significant.

In synchrocyclotrons (i.e., phasotrons which represent cyclotrons with a varying frequency of the electric field according to the ideas of Veksler and later of McMillan), with the aid of which we can attain relatively higher energies of the particles, the radiation again proves to be insignificant. The maximum energy of the particles in this case is basically determined by technical difficulties connected with the formation of large magnets and the modulation of frequency.

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For the betatron, a relativistic apparatus (i.e., an apparatus in which relativistic variation in mass does not disrupt the operation of the apparatus) the radiation of electrons rotating in a circular fixed orbit limits the maximum attainable energies. Attention was first brought to this case in 1944 by Soviet physicists.

For a linear resonating accelerator or a wave-guide accelerator, the maximum attainable energy is not directly connected with the radiation of accelerated particles, but for a microtron and synchrotron (first set forth by V. I. Veksler), this radiation is essential. The influence of radiation on the operation of these devices will be examined below.

Radiation of a Single Electron

Let us introduce the formula describing the radiation of a single relativistic electron moving in a magnetic field. We shall proceed from the classical relativistic equation of electron motion, containing a term which takes into account radiational "stoppage" (or, what is essentially the same, from the classical nonquantum Lawrence-Dirac equation for a point electron):

$$m\frac{du_i}{ds} = \frac{e}{c}F_{ik}u_k + \frac{2}{3}\frac{e^2}{c^3}\left\{\frac{d^2u_i}{ds^2} + u_i\left(u_k\frac{d^2u_k}{ds^2}\right)\right\},\quad (i, k = 1, 2, 3, 4), \tag{1}$$

where m is the invariant mass of the electron, e the electron charge, c the velocity of light, u_i the components of four-dimensional velocity, F_{ik} the tensor of the electromagnetic field $[H(F_{23}, F_{31}, F_{12}), iE(F_{14}, F_{24}, F_{34})]$ and $ds = dt\sqrt{1-\beta^2}$ where as usual $\beta = \frac{v}{c}$. The summation convention is denoted by indexes that occur twice.

Rewriting equation (1) for the values i = 1, 2, 3, and for i = 4 we get the equation for momentum and energy

$$\frac{dp}{dt} = e\left(E + \left[\frac{v}{c}H\right]\right) + \frac{2}{3}\frac{e^2}{c^3}\left\{\ddot{v} + \frac{3}{c^2}\frac{\dot{v}(v\dot{v})}{1-\beta^2} + \right.$$
$$\left. + \frac{v}{c^2(1-\beta^2)}\left(v\ddot{v} + \frac{3}{c^2}\frac{(v\dot{v})^2}{1-\beta^2}\right)\right\}\frac{1}{1-\beta^2}, \tag{2}$$

$$\frac{d\mathfrak{E}}{dt} = e(vE) + \frac{2}{3}\frac{e^2}{c^3}\left(\frac{v\ddot{v}}{(1-\beta^2)^2} + \frac{3}{c^2}\frac{(v\dot{v})}{1-\beta^2}\right). \tag{3}$$

In these formulas $p = \frac{mv}{\sqrt{1-\beta^2}}$ is the momentum of the particle, v the velocity of the particle, $\mathfrak{E}$ the energy of the particle, E and H the electrical and magnetic field strengths.

As a zero approximation to the solution of equation (3), we shall take the solution of the equation without considering radiational damping.

$$\frac{dp}{dt} = e\left(E + \left[\frac{v}{c}H\right]\right). \tag{4}$$

We shall now examine the problem without the electrical field, i.e., when E = 0. Assuming that the magnetic field does not change the absolute magnitude of the velocity, we will have from (4)

$$\dot{v} = \frac{e}{m}\sqrt{1-\beta^2}\left[\frac{v}{c}H\right] \tag{5}$$

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and consequently

$$\ddot{v} = \frac{e^2}{m^2}(1-\beta)^2\left[\left[\frac{v}{c}H\right]H\right]. \tag{6}$$

Inserting (5) and (6) in (3), we will obtain (since $v\,\dot{v} = 0$)

$$\frac{d\mathfrak{E}}{dt} = \frac{2e^2}{3c^3}\left\{\frac{v\left[\left[\frac{v}{c}H\right]H\right]}{(1-\beta^2)^2}\,\frac{e^2}{m^2}(1-\beta^2)\right\} =$$

$$= -\frac{2e^2}{3c^3}\cdot\frac{e^2}{m^2c}\cdot\frac{1}{1-\beta^2}[vH]^2.$$

This equation can be rewritten in the form

$$r_0^2[vH]^2\left(\frac{\mathfrak{E}}{mc^2}\right)^2, \tag{7}$$

having in mind that $\mathfrak{E} = \frac{mc^2}{\sqrt{1-\beta^2}}$ and $r_0 = \frac{e^2}{mc^2}$ (the classical radius r_0 of the electron). Formula (7), which determines the electron losses in radiational damping in the magnetic field, was obtained by I. Ya. Pomeranchuk (7) in a work devoted to the movement of cosmic electrons in the earth's magnetic field (published in 1940). It can equally be used to find the radiation of a single electron moving in an accelerator. The problem of the interaction of electrons in accelerators will be examined separately. Since in the accelerator (for example, in a betatron) v is perpendicular to H and motion takes place along the circular radius $R = \frac{\mathfrak{E}}{eH} = \frac{c}{\omega}$ (the latter equality assumes that the velocity of electron motion is close to the velocity of light), then from (7) we obtain the energy which is radiated per unit path length:

$$\mathfrak{E}' = -\frac{2}{3}r_0^2H^2\left(\frac{\mathfrak{E}}{mc^2}\right)^2. \tag{8}$$

For the radiation in one revolution, we get

$$\mathfrak{E}'' = -\frac{4\pi}{3}\frac{e^2}{R}\left(\frac{\mathfrak{E}}{mc^2}\right)^4. \tag{9}$$

It is clear from formula (8) that the radiation of the particle (up to this time the matter concerned only the electron for definiteness) for one revolution is proportional to the square of the mass of the particle. From formula (9) it is clear that the radiation in one revolution is proportional to the fourth power of the energy of the accelerated particle.

Let us evaluate the maximum attainable energy of the accelerated particle in the betatron. It is obviously determined by the condition that the energy obtained from the accelerator in one rotation is completely dissipated in radiation. The energy acquired by the particle in the betatron in one revolution is equal to

$$e\oint E\cdot ds = e\cdot 2\pi R\cdot E. \tag{10}$$

On the other hand, according to Maxwell's equation

$$\oint E\cdot ds = -\frac{1}{c}\frac{\partial\Phi}{\partial t},$$

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where $\Phi = \pi R^2 \overline{H}$ is the magnetic flux ($\overline{H}$ is the average intensity of the magnetic field in the area of the circle enveloping the orbit). Since under the conditions of a stationary orbit it is necessary that $\overline{H} = 2H_0$, where H_0 is the intensity of the magnetic field at the orbit, then (10) can be rewritten in the form

$$\oint E \cdot ds = -\frac{e}{c} \pi R^2 2 \dot{H}_0,$$

whence for the loss per unit path length we get the expression

$$\mathcal{E}' = -\frac{e}{c} R |\dot{H}|. \qquad (11)$$

Equating expressions (8) and (11)

$$\frac{2}{3} r_0^2 H^2 \left(\frac{\mathcal{E}}{mc^2}\right)^2 = \frac{e}{c} R |\dot{H}|,$$

we get for the critical value of the energy $\mathcal{E}_c$:

$$\mathcal{E}_c = mc^2 \left(\frac{3eR}{2r_0^2 c} \frac{\dot{H}}{H^2}\right)^{1/2}. \qquad (12)$$

It is clear from this that the maximum electron energy in the betatron increases as the rate of change of the magnetic field $\dot{H}$ increases; for a given value of H, the quantity $\mathcal{E}_c$ is proportional to the square root of the energy quantity acquired per unit path length.

Formula (12) was obtained in 1944 by Ivanenko and Pomeranchuk (6). As the authors showed, with reasonable assumptions concerning R and H, values of the order of 500 Mev are obtained for the energy $\mathcal{E}_c$. This energy obviously is the maximum obtainable for electrons accelerated in a betatron (described more fully in (8)).

Of significant interest is the determination of the angular distribution and radiation spectrum of an electron in the betatron. These problems are examined in the works of Artsimovich and Pomeranchuk (8), and of Schiff (9) who based his work on Schwinger's. The results of these works generally agree with each other. We will set them forth, according to Schiff.

The electron motion in the betatron is periodic. Therefore, one can expect the presence, in the radiation spectrum, of harmonics; that is, multiples of the basic cyclic frequency (angular velocity) of the electron around the orbit: $\omega_0 = \frac{eHc}{\mathcal{E}}$ For the total energy, coming from the radiation of the nth harmonic, we have the formula

$$w_n = \frac{\omega_0 e^2 n}{R} \left\{ 2\beta^2 J'_{2n}(2n\beta) - (1-\beta^2) \int_0^{2n\beta} J_{2n}(x)\, dx \right\}, \qquad (13)$$

where J_{2n} is the Bessel function of the 2n order and of the first kind, and J'_{2n} is its derivative. Expression (13) was obtained by Schott in 1911, who purely academically and without any applications of the theory of accelerators examined problems relating to the radiation of moving charges, in particular the radiation of charged particles moving in a circular orbit. Formula (13) contains the following results in unresolved form, obtained not long ago by Artsimovich and Pomeranchuk (8), and Shwinger (10): w_n grows at the rate $n^{1/3}$ as n increases to a value of the order $\left(\frac{\mathcal{E}}{mc^2}\right)^3$, and then exponentially decreases (Figure 1):

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$$\left.\begin{aligned} W_n &\approx 0{,}518\,\frac{\omega_0 e^2}{R}\,n^{1/3} \text{ for } 1 \ll n < n_0, \\ W_n &\approx e^{-n/n_0} \text{ for } n > n_0, \\ n_0 &\approx \left(\frac{\mathfrak{E}}{mc^2}\right)^3. \end{aligned}\right\} \qquad (14)$$

From formula (14) it is clear that the basic part of the radiation comes at the higher harmonics $[n \sim (\frac{\mathfrak{E}}{mc^2})^3$; for example, for a betatron accelerating a particle to energies of 100 Mev in a field $H \sim 10^4$ oersteds, we have $n_0 \sim 10^7$, from which it immediately follows that a significant part of the radiation occurs in the visible spectrum]. It can be concluded from this that the radiation can also be observed visually. A few words can be said about the angular distribution of radiation. If polar angles ξ and η are introduced so that $\xi = 0$ is the instantaneous direction of the moving electron and $\eta = 0$ is the orbit plane (Figure 2), then the angular distribution of radiation will be determined by the formula.

$$\frac{\omega e^2\beta^3}{4\pi R}\left[\frac{1}{(1-\beta\cos\xi)^3} - \frac{(1-\beta^3)\sin^2\xi\cos^2\eta}{(1-\beta\cos\xi)^5}\right]. \qquad (15)$$

It can be ascertained that the integral of this expression over a sphere gives the total value of the radiated energy corresponding to (7). From formula (15) it is immediately seen that, for $\mathfrak{E} \gg mc^2$ and consequently $\beta \approx 1$, the radiation is concentrated in the solid angle whose axis is along the instantaneous direction of motion, and with an angular "opening" of the order $\frac{mc^2}{\mathfrak{E}}$ radians. The angular distribution of radiation per radian averaged around the whole circumference, has the form

$$\left(\frac{\omega e^2\beta^2}{8\pi R}\right)\frac{\left[1+\cos^2\vartheta - \frac{\beta^2}{4}(1+3\beta^2)\sin^4\vartheta\right]}{(1-\beta\sin^2\vartheta)^{7/2}}, \qquad (16)$$

where ϑ is the polar angle, selected so that $\vartheta = 0$ is perpendicular to the orbit plane. When $\beta \ll 1$, we have an angular distribution determined basically by the ordinary coefficient $(1+\cos^2\vartheta)$. Thus, the relativistic radiation ($\mathfrak{E} \gg mc^2$) of a single electron is basically concentrated close to the orbit plane in a small solid angle oriented in the direction of electron motion (that is, the electron radiates forward in the direction of motion). Since the formation of overtones (harmonics) is connected with the irregularity of electron radiation for a given point of observation at various positions in the orbit, most of the harmonics are also concentrated in the orbit plane. The intensity of radiation coming from the n^{th} harmonic rapidly decreases with increase in distance from the orbit plane. In a direction perpendicular to the orbit plane only the basic frequency ω_0 is radiated, equal to the cyclic frequency of electron orbital rotation.

It is also easy to determine the direction of polarization of the radiation of an electron moving in a circle. Observing the motion of an electron in its orbit plane, we see only its oscillations, perpendicular to the direction of observation, i.e., the dipole lying in the orbit plane. Consequently, the radiation is polarized in the electron's plane of motion.

Radiation of Electron Systems in the Betatron

Up to this time, we have examined the radiation of a single electron moving in a magnetic field. In all accelerator mechanisms, including the betatron, we always have to deal with combinations of interacting particles. Therefore, questions naturally arise on how interaction of electrons influences their over-all radiation, and in what cases can the considerations be applied relative to one electron. We will note here that it is not immediately obvious that the electron current in the betatron will radiate since a constant circular current does not radiate.

We will set forth briefly the results of examining this problem. The calculation of the interference effect of the radiation of N individual electrons is accomplished in the usual way. The expression for the energy coming from the nth harmonic of the spectrum is multiplied by a coefficient of the form

$$F = \left| \sum_{s=1}^{N} \exp(in\varphi_s) \right|^2, \tag{17}$$

where φ_s is the angular coordinate of the sth electron. Summation is carried out over all the electrons. The coefficient (17) leads to three essentially different cases.

Case 1 -- The particles are distributed along the circumference at angular distances from each other $\left(\frac{2\pi}{N}\right)$. In this case, the coefficient F will equal zero for all harmonics for which $\frac{n}{N}$ is not a whole number. This follows directly from the rule governing the vector addition of complex numbers. In this case, if $\frac{n}{N}$ is a whole number, the coefficient F equals N^2, since each of the components of exp (in φ_s) in this case is equal to unity. Thus in the examined case the radiation can be decreased if we make $N > n_0$ (we will recall that n_0 signifies that harmonic after which the exponential drop of the radiation energy begins). We will note, however, that the case $N > n_0$ corresponds to a great current density in the electron beam and can scarcely be realized. In addition, it is difficult to visualize a concrete physical condition in which such a uniform distribution of electrons along the circumference could exist.

Passing, in formula (17), to the limit $N \to \infty$, which in practice corresponds to the case of a constant current, we can conclude that a constant circulatory current does not radiate, since

$$\int_0^{2\pi} \exp(in\varphi)\, d\varphi = 0.$$

We have already noted the importance of this case.

Case 2 -- The particles are randomly distributed within the beam, occupying an angle of φ radians in the orbit, which corresponds to the motion of a group of electrons. In this case, the coefficient (17) will have the form

$$F \sim N + (N^2 - N) f(n\varphi), \tag{18}$$

where $f(0)=1$ and $f(x)$ decreases when $x > 1$, the nature of the decrease depending on the average density ρ of the electrons in the beam. The angular interval φ is determined as that interval in which the density of the electron group falls e times. It is assumed that the density of the electrons in the group changes according to Gauss's law. A similar distribution of electrons in the orbit in the form of groups takes place in the synchrotron.

From (18), it follows that the [illegible] energy losses connected with the existence of the group develop in the harmonics $n \lesssim \frac{1}{\varphi}$ (in such a way that $x = n\varphi \lesssim 1$) and correspond to wave lengths $\lambda \gtrsim$ dimensions of the group.

Case 3 -- The electrons are randomly distributed along the whole circumference. It is easy to see that, because the angular coordinates φ_s of the individual electrons [illegible] will drop out and we will find that the coefficient is $F = N$.

The physical picture corresponding to this case is as follows: In the electron beam, density fluctuations $\Delta\rho$ take place. If the density of the current in the beam is not large, then the fluctuations will also be small. Therefore they can be considered independent (since they create weak fields). For independent fluctuations, Poisson's law relating to random chance quantities gives

$$\Delta\rho \sim \sqrt{N},$$

where $\Delta\rho$ is the fluctuating electron density in the beam and N is the concentration of electrons in the beam.

The radiation of individual fluctuations will be proportional to $(\Delta\rho)^2 \sim N$. For a full beam, summing up over all the fluctuations, we also derive that the radiation from the fluctuations is approximately N, which coincides with the above result. In this manner, namely the presence of fluctuations accompanying the attainment of high electron energy, electron radiation in the betatron is created. (The role played by density fluctuations of charge in the radiation of electron rings was noticed in the discussions of D. Ivanenko and Ya. Terletskiy in 1945.)

In their paper, Artsimovich and Pomeranchuk make an approximate evaluation of the limits of applicability of the conception of noninteracting electrons in the betatron. It is obvious that electrons can be considered noninteracting and their density fluctuations as independent (i.e., following Poisson's law), if the maximum potentials corresponding to the fluctuations are small in comparison with the differences in kinetic energy of the orbital electrons. The differences in kinetic energies is brought about for two reasons: nonsimultaneous admittance of electrons into the working area and the collisions of electrons with gas molecules (ionization losses). Comparing the magnitudes of fluctuating potentials (which, according to Artsimovich and Pomeranchuk, are around 60 eV) and the magnitudes of the differences in electron velocities (the differences average 10^3 eV), the authors concluded that the influence of electron interaction on radiation can be disregarded in the betatron.

Influence of Radiation on the Operation of Various Accelerators

1. Betatron (11, 12, 13)

As was shown above, the over-all energy losses in radiation are proportional to the number of electrons in the beam. Calculations show that even at electron energies of 100 Mev contraction of the radius of the stationary orbit can be expected. For energies $\mathcal{E}$ of the order of 300 Mev (the frequency of variation of the magnetic field is $\frac{\omega}{2\pi} = 60$ cps ; the radius of the stationary orbit is $R = 2m$; and the field strength at the orbit is $H_{max} = 5000$ gausses) the losses are 4.7 percent of the total energy of the electron, if the field varies harmonically. The greater part of the energy comes at a wave length of $2\pi R \left(\frac{mc^2}{\mathcal{E}}\right)^3$, which corresponds approximately to 600 angstroms; i.e., it lies far in the ultraviolet region.

It follows from this that energy losses cannot be significantly decreased by shielding. (By shielding is meant the use of a metallic surface of high conductivity on which currents arise, induced by the electron current, whose radiation compensates for the radiation of the main current.) Compensation, obviously, is possible only in the case of the coherence of these currents which places conditions on the wave length $\lambda \gg R$.

It should be noted that, in a close examination regarding the work and construction of betatrons in Germany, it appeared that designers kept in mind the radiation of electrons in the betatron and therefore built a special model for studying such radiation before undertaking the construction of a betatron of 200 Mev (the latter was not completed because of the war).

2. Synchrotron (16, 17)

In the synchrotron the electrons are admitted to the apparatus in individual packets, each of which corresponds to the beginning of a period of increasing magnetic field strengths. The electrons move in it in a circular orbit in the form of packets with a certain amount of spread. Even though at first sight it appears that in this case coherent radiation should take place and the intensity should be proportional to the square of the number of electrons in the packet, actually calculations show that the maximum radiation occurs at such short waves (in comparison with the length of the packet) that this radiation is again noncoherent.

For groups having a spread of the order of tens of degrees, the main part of the radiational spectrum has the same intensity as the intensity of radiation of the complete ring of electrons which are randomly distributed along the circumference (we must remember that in this case the intensity is proportional to the total number of electrons). Coherent radiation comes at a wave length of an order of magnitude of the linear dimensions of the packet. Coherent radiation occurring in one electron is proportional to the number of electrons and is not dependent on the electron energy in the assumption $\mathcal{E} \geqslant mc^2$. In the absence of shielding, this energy is given by the formula

$$1.4\,\omega_0 T\left(\frac{e^2}{R}\right)\left(\frac{N}{\varphi^{4/3}}\right), \tag{19}$$

where T is the acceleration time of the electron and φ the angular spread of the group in radians. Equation (19) assumes that the density distribution is according to Gauss's law and φ is measured between the points in which the density is e^{-1} times maximum density.

For $\mathcal{E}$ of the order of 300 Mev, then $N \sim 10^{11}$ and $\varphi = 0.2$ ($\sim 12^{\circ}$), the losses due to coherent radiation of the group are about 40 times higher than the losses connected with the radiation of the complete ring of randomly distributed electrons. However, by shielding the electron beam this radiation can be significantly reduced.

In the above example, packet losses in coherent radiation can be reduced, with the aid of shielding, to one-tenth of the radiation losses of the full ring of electrons (in the absence of shielding).

In comparison with the betatron, the synchrotron has the advantage in that the radiation losses can be compensated for by automatic focusing of the electrons while moving in the orbit, which possesses phase stability. The only requirement which has to be satisfied here is that the losses of the radiating electron in a rotation period be small in comparison with the energy which is acquired in passing the accelerating electric gaps. Schiff indicated that with the aid of the synchrotron, electron energies of 10^3 Mev could probably be attained.

3. Microtron (18)

The microtron is an accelerator apparatus consisting of an "endo-oscillator" and a magnetic field. The electrons, accelerated by varying potentials in the endo-oscillator, are rotated by the magnetic field in circles of ever-increasing radii. For normal operation of the microtron it is also necessary that the radiation losses in one rotation should be smaller than the voltage on the "dueemts" (dees). Thus, even here radiation limits the attainable energies approximately to the same degree as in the synchrotron.

4. Linear Resonance Accelerators (7)

The linear resonance accelerator represents a system of a great number of oscillating circuits (resonators) of high quality; i.e., small attenuation. Electrons, moving along such a system of resonators, fall each time into the accelerating phase of the corresponding resonator, which brings about an increase in their energies. As they accelerate, the electrons radiate. It can be shown, however, that in the rectilinear motion of charges in the accelerating electric field the ratio of radiated energy to that acquired is insignificantly small. Therefore, radiation losses in a linear resonance accelerator do not limit the attainable energies. We must note, however, that for the attainment of high energies it is necessary to create an accelerator of considerable dimensions; thus, to obtain electrons with energies of 300 Mev, the dimension of the apparatus would have to be about 450 meters.

For heavy particles, the length of the linear resonance accelerator has a more modest size of the order of decameters, in order to obtain particles with energies of about 100 Mev. In a linear accelerator for heavy particles, radiation plays even a smaller role than in linear accelerators for electrons, because the radiation is in reverse proportion to the mass of the accelerated particle.

5. Linear Wave-guide Accelerator

The idea of operation of the linear wave-guide accelerator is to accelerate particles by magnetic waves scattered throughout the system, whose phase velocity is close to the velocity of light. Radiation losses here will also be very small for the same reasons as in the preceding cases. With the use of a wave-guide accelerator, electrons with energies of 10^3 Mev can be obtained.

6. Synchrocyclotron

The synchrocyclotron, or phasotron, is a cyclotron which operates in a manner similar to that of the synchrotron.

In the phasotron, the frequency of the alternating voltage on the "duants" (dees) is modulated by a somewhat lower frequency which corresponds to the periods of admittance into the apparatus of the accelerated particles. By a correct selection of the moment of admission, the motion of the particles possesses phase stability (just as in the synchrotron), regardless of relativistic variation in mass of the particles. This apparatus was developed for the acceleration of heavy particles (ions, alpha particles, deuterons, and others). Even though the relativistic effect of mass variation has a noticeable influence, the velocities of the accelerated particles are noticeably different from the speed of light c (the phasotron at Berkeley accelerated alpha particles to energies of 400 Mev, to reach a maximum velocity of 0.45 c). Therefore, the radiation of the charged particles in this cyclotron can be calculated according to nonrelativistic formulas. This radiation has no significant effect on the performance of the apparatus, if one considers that the radiation is in inverse proportion to the mass of the particle, which is relatively very large for heavy particles.

Experimentally Observed Effects Connected With Electron Radiation. "Luminescent Electrons"

Previously, in Blewett's (15) work with the betatron at 100 Mev, the following two experimental facts were shown. First, it was observed that the accelerated particles had compressed orbits which caused the particles to strike the target sooner than would have happened in the absence of radiation. Secondly, the above-indicated compressed electron orbits were the same for various values of total current in the beam. This brings out the independence of the radiation of each electron from the number of electrons in the beam. Blewett emphasized that he did not observe the radiation itself. He studied with special care the microwave region of radiation in which, according to his calculations, the main portion of the radiation in the apparatus should occur. However, as we showed above, at energies 100 Mev. the maximum electron radiation occurs at the high harmonics which correspond to the visual or even ultraviolet part of the spectrum. Therefore, it is natural that Blewett could not distinguish any radiation in the microwave region, even though he worked with very sensitive indicators, capable of detecting radiations of 10^{-5} watts. (The possible reason why Blewett was not able to observe the visible radiation was that in the 10-Mev betatron with which he worked, the walls of the vacuum chamber were silver-plated (21).)

In the summer of 1947, there appeared a short memorandum by Pollock (5) and his collaborators entitled "Visual Observation of the Radiation of a Beam of Electrons in a Synchrotron at 70 Mev." The electron orbit of the synchrotron had a radius of 29.[illegible] cm. The radiation was seen as a small bright speck of white light on the glass surface of the vacuum tube, if one looked into the plane of the orbit toward the approaching electron.

In a normally operating synchrotron, the electrons striking the target create X-ray "stoppage" radiation with a power of 50 roentgens per minute at a distance of one meter. For this intensity of X-ray radiation, the spot was very bright; however, even at intensities equal to one roentgen per minute at a distance of one meter, the spot could still be observed in daylight. With the introduction of coils which disturbed the electron orbits so that the electrons struck the target up to the maximum attainable magnetic field, the intensity of the observed illumination increased sharply with increase in electron energy, if this energy surpassed 30 Mev. If the electrons struck the target after attainment of the maximum magnetic field, then the intensity of illumination did not depend on the energy with which the electrons left the beam, but was determined by the maximum energy acquired by the electrons.

The visually observed effect disappeared if the electrons struck the target with energies less than 30 Mev. If, with the aid of a special resonator inserted for a short time before maximum magnetic field strength, the electron beam is displaced to a radius smaller than the inner radius of the target, then with a further increase in magnetic field strength, the electron orbit will be widened. In addition, instead of the small speck, the observer will see a short line in the orbit plane. The emitted radiation is polarized; that is, the electrical vector lies in the orbit plane. With a 90-degree rotation of the Nicol prism, the visually observed illumination disappeared.

Pollock did not give information on the spectral composition of the radiation, but promised to present soon a detailed account of the experiments conducted.

Excellent photographs of the new effect "luminescent electron" appear in a number of recent journals (19, 21, 22).

Conclusions

Thus the presence of electron radiation in accelerators of the betatron type, first predicted by Soviet physicists, has been very quickly substantiated by a series of experiments topped off by direct observation of the "luminescent electron" by Pollock's followers. This phenomenon represents a new physical effect which characterizes electrons with 100 Mev energies and permits one to "see" the electron directly.

The phenomenon of the luminescent electron exists for the accelerators of electrons (betatron, synchrotron). It can be said that the synchrotron and betatron are, first, generators of "stoppage" radiation (gamma-quanta) and, secondly, generators of ordinary illumination (luminescent electron), independent of their use as generators of accelerated particles.

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It is difficult to say now what application in science this effect will have. However, there is no doubt that a new physical effect has been experimentally uncovered. In the theoretical prediction of this effect, a prominent part was played by Soviet physicists.

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[Figures follow]

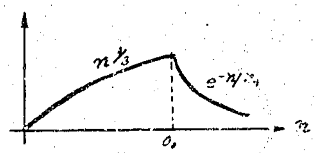

Figure 1. Dependence of the Energy Coming From Nth Harmonic on the Number of the Harmonic

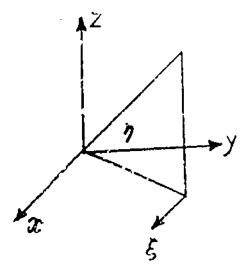

Figure 2. System of Coordinates Used in Formulas (14)-(16)

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